Interface engineered Josephson junctions optimized for high J_C

Hisashi Shimakage, Ronald H. Ono and Leila R. Vale

***Abstract*—High temperature superconducting interface engineered junctions were fabricated using $YBa_2Cu_3O_{7-X}$ on $LaAlO_3$ (LAO) and sapphire substrates. We report on the improvements in the electrical characteristics by junction narrowing. Originally, the 2 μm wide junctions had high critical current densities of $1.2x10^6$ A/cm^2 at 4.0 K and showed wide junction effects. Narrowing the junctions to below a micrometer reduced the wide junction effect over a large range of temperatures and the junctions had characteristics voltages of 5.16 mV at 4.0 K. The magnetic-field modulation of the critical current was also more ideal after narrowing. Furthermore, we show that interface engineered junctions on sapphire substrates have similar characteristics to those on LAO.**

***Index Terms*—interface engineered Josephson junction, sub-micrometer width, wide junction effect, $YBa_2Cu_3O_{7-X}$.**

I. Introduction

FOR applications at high speed and high frequency, high-T_C superconducting (HTS) Josephson junctions must have several high quality properties. Junction parameters such as critical current I_C and normal resistance R_N should be reproducible for large-scale integrated circuits [1]. Furthermore, the characteristic voltage, $Vc = I_C R_N$, must be high for microwave applications such as THz mixing [2]. As $YBa_2Cu_3O_{7-X}$ (YBCO) has a large gap energy, ideal YBCO Josephson junctions should have high $I_C R_N$ products. After the discovery of HTS materials, many types of Josephson junctions were proposed [3]. The current-voltage (I-V) characteristics usually show resistively-shunted junction (RSJ) behavior, but junctions with good reproducibility and high $I_C R_N$ products are not yet routinely achieved. The ramp-edge junction was an attractive device type with good controllability and uniformity but relatively low resistance-area products, $R_N A$ [4]. Moeckly and Char developed the interface-engineered junction (IEJ) as an alternative type of ramp-edge junction, with both good reproducibility and large $R_N A$ [5]. The barrier of the IEJ is formed by vacuum annealing and ion-beam or plasma irradiation, and is thought to be a different crystalline form of YBCO.

Several groups are now working on the interface modification process as well as ramp-edge junctions with deposited barriers [6]-[8]. A common feature of many of these junctions is the relationship $V_C \propto J_C^{1/2}$, where J_C is the critical current [3]. Therefore, for high-frequency applications, we should make junctions with large current densities. However, as discussed in more detail in § II-C, large J_C results in a large effective electrical width for the junctions. This leads to non-ideal and undesirable behavior.

We report a junction fabrication process for IEJs with *in-situ* vacuum annealing and an optimization procedure. Because our junctions have large critical current densities, they exhibit wide-junction effects at the original width of 2 μm. To produce junctions with more ideal, point-like characteristics, we ion-milled the junctions to reduce their physical width. These results show that the narrowed junctions are indeed more ideal. Finally we have made these junctions on sapphire substrates, which have excellent microwave and optical properties.

II. Experimental Procedure

A. IEJ Fabrication on LAO

Our first YBCO interface-engineered junctions were fabricated on $LaAlO_3$ (LAO). The base YBCO and insulating $SrTiO_3$ (STO) were grown by 120 mJ KrF pulsed-laser deposition. The 180 nm YBCO films were deposited at 770 °C with 104 Pa of O_2. The 260 nm STO films were deposited at 730 °C with 53 Pa of O_2. The critical temperature of the YBCO film was 90 K. After the YBCO/STO bilayers were patterned by photolithography, they were etched by Ar ion milling at 300 V at an angle of incidence of 45º. After the photoresist was removed, the samples were cleaned in acetone with ultrasonic agitation and mounted in the deposition chamber. The samples were heated to 400 °C – 500 °C in vacuum, and annealed for 30 min. This vacuum anneal controls the junction's critical current density. Then O_2 at 800 Pa was introduced into the deposition chamber, and the sample was heated to YBCO's deposition temperature at the rate of 25 °C/min. Finally, 180 nm YBCO and 200 nm STO were deposited for a counter-electrode. The deposition conditions were the same as those of the base electrode. The STO was used as a passivation layer. The sample was patterned to form the 2 μm wide edge junction, and etched by Ar ion milling at 90º incident to the sample. Contacts were

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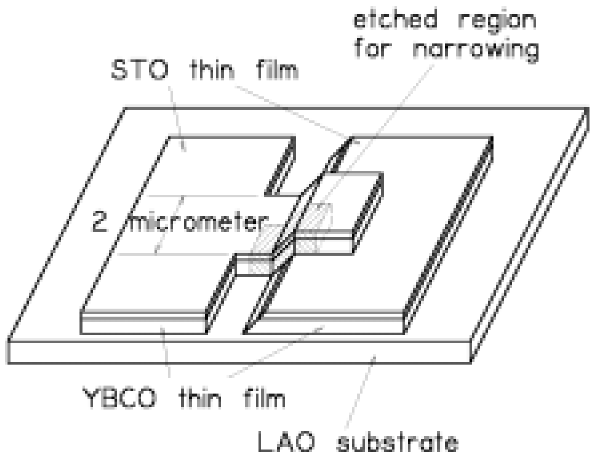

Fig.1. Schematic drawing of IEJ structure with narrowed region.

made by ion milling vias through the STO, oxygen-plasma cleaning the exposed YBCO, and evaporating 200 nm Au pads. Typical critical temperatures were 88 K for base electrodes and 85 K for counter-electrodes. To reduce the junction width, the sample was covered with photoresist and patterned to open windows for ion milling to remove part of each junction. Fig. 1 shows a schematic drawing of the IEJ with the narrowed region. The edge angle and junction size were measured by atomic force microscopy.

B. IEJ Fabrication on Sapphire Substrate

Our process of fabricating IEJs on sapphire substrates was the same as that for LAO substrate except for a CeO_2 buffer layer. Before deposition of the base electrode, a 100 nm thick CeO_2 thin film was deposited by KrF laser ablation. The typical critical temperature of YBCO on a sapphire substrate is 89 K. During the ion milling of the base electrode, the etching time was adjusted so as not to remove all of the CeO_2 thin film. The remaining exposed CeO_2 then acts as a buffer layer for the counter electrode.

III. Results and Discussion

A. Current-Voltage Characteristics

Typical I-V characteristics for anIEJ on LAO measured at 50 to 70 K are shown in Fig. 2(a), and for the same junction, after narrowing, in Fig. 2(b). The width of the narrowed junction was 0.9 µm. The calculated current density for the 2 µm junction is $1.2\text{x}10^6$ A/cm^2 at 4.0 K. This value is higher than those reported for IEJs by other groups [5]-[8]. The I-V characteristics of the 2 µm junction showed high-bias rounding over the entire temperature range. Wide junctions, with junction phase varying across the width of the junction, have characteristics that are dominated by motion of Josephson flux which motion can occur when the junction is wide compared to the Josephson penetration depth λ_J, where $\lambda_J=(h/4\pi e\mu_0 J_C t)^{1/2}$ [9]. Using the calculated value of J_C from the I-V characteristics and typical values for λ_L of 310 nm for our YBCO films, we found λ_J to be 0.54 nm at 70 K. The

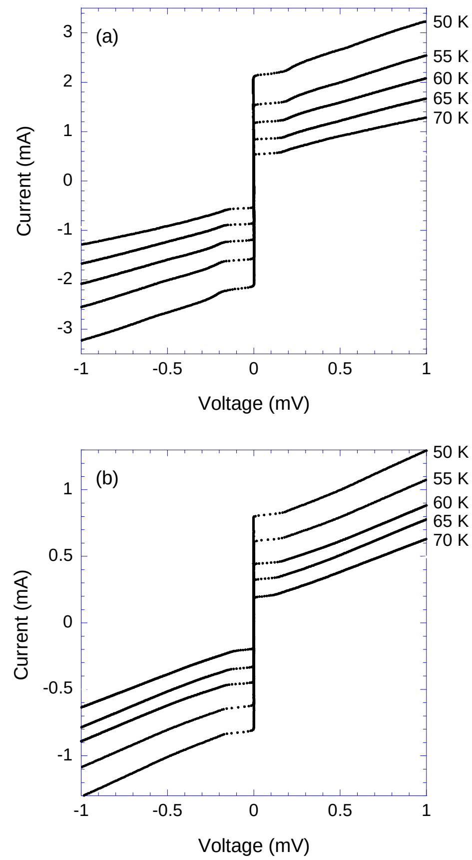

Fig. 2. Current-voltage characteristics at 50-70 K for a junction (a) before narrowing and (b) after narrowing.

simple RSJ model applies to only to a point-like junction with width W < $4\lambda_J$. As the 2 µm width is nearly equal to $4\lambda_J$ at 70 K, the junction should behave as a wide junction below 70 K. This is consistent with experimental behavior, including the excess current and the rounding at high bias. In contrast, the I-V characteristics of the narrowed junction are closer to those of ideal RSJ-type junctions. The narrow-junction condition (W < $4\lambda_J$) is consistent with the junction's width of 0.9 µm above 40 K, where λ_J=0.27 µm. For applications requiring good microwave response, narrow junction characteristics are needed. Features such as Shapiro steps are reduced in a junction where the junction phase varies across the geometry. We have measured and reported elsewhere on the step response of a narrow junction [10].

B. $I_C R_N$ product and magnetic field modulation

Fig. 3 shows the temperature dependence of the $I_C R_N$ products before and after the narrowing process. All of the narrowed junctions exhibit the same behavior as in Fig.3. The characteristics have the quasi-linear dependence shown by many types of YBCO junctions, including IEJs made by other groups [11]. The $I_C R_N$ products below 30 K are higher than the original values, with $I_C R_N$ of 5.16 mV at 4.0 K, the highest value yet reported for IEJs. As Fig. 3 demonstrates, a characteristic frequency $f_C=2eV_C/h$ of 1 THz can be achieved at over 40 K, where the wide-junction effects should not play

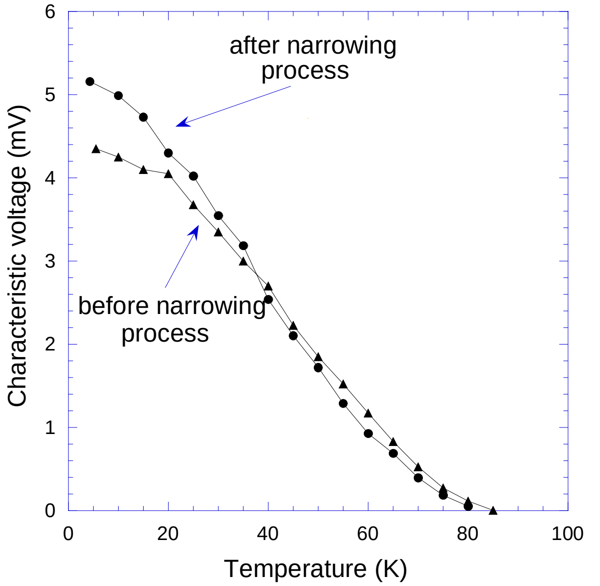

Fig. 3. Product of critical current-normal resistance as a function of temperature (a) before narrowing, and (b) after narrowing.

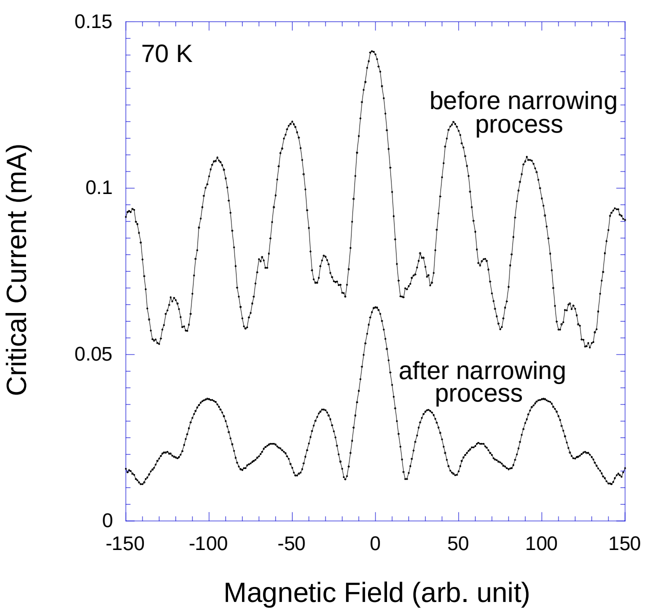

Fig. 4. Junction critical current as a function of magnetic field at 70 K.

a role.

Fig. 4 shows the dependence of the critical current on magnetic field at 70 K for a junction before and after narrowing. We observed periodic modulation with relatively large excess current in the 2 µm junction. On the other hand, the behavior for the narrowed junction was closer to a point-like response pattern [9] with small excess current. Note that the two curves in Fig. 4 are not offset; the background current is noticeably smaller in the narrow junction. Although we have not yet analyzed the magnetic-field modulation

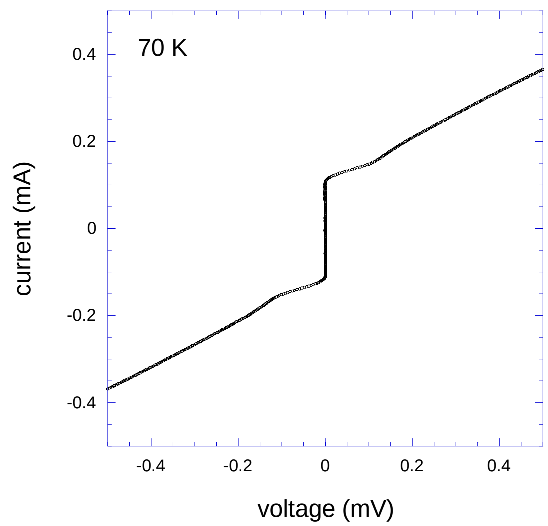

Fig. 5. Current-voltage characteristics for a junction on sapphire substrate at 70 K.

quantitatively, these results suggest that the narrowing process yields junctions with more ideal characteristics.

These experiments verify that many of the features of HTS junctions are due to simple, wide-junction effects. Clearly, with the desire for large f_C in mind, it is necessary to design junctions with linewidths at the 1 µm level or smaller. This has implications for junction reproducibility and spreads. Smaller linewidths (especially using optical lithography) can lead to less control of junction area with correspondingly larger spreads in critical current and normal resistance. Another danger is that the smaller junctions may suffer from environmental degradation more quickly, because of the possibility of attack of the junction area from the edges.

C. Junction stability

Due to the concern raised above, we investigated the long-term stability of our 2 µm IEJs. We stored the junctions in a room air environment, with no special care taken. It should be noted that the relative humidity in this environment rarely increased above 40%. After 10 months, the average critical current decreased 10%, but the normal resistance increased also by 10%. As a result, $I_C R_N$ products remained the same. We infer that the edge of the junction was exposed to normal air, and a small amount of the junction area was degraded. This result is quite good compared with other HTS junctions. We believe that careful storage or application of a passivation layer will protect the junctions for a longer time.

D. IEJ on sapphire substrate

Fig. 5 shows the I-V characteristic of a 2 µm wide IEJ on a sapphire substrate at 70 K. The critical current is 100 µA and the normal resistance is 2 Ω. Although the fabrication process for the barrier and the counter electrode is not yet optimized, all of the junctions on the chip showed RSJ-like properties.

The junction properties are very similar to those on LAO, including $V_C(T)$. We have not yet made narrower junctions, but expect that the results obtained on LAO will be reproduced on sapphire. Since sapphire is a good material for microwave applications, junctions with high I_CR_N products on sapphire should be good devices for use as THz mixers. We are now improving the junction process to optimize these junctions for mixers and other high-frequency applications.

IV CONCLUSION

We have fabricated interface engineered junctions on LAO and sapphire substrates using *in situ* vacuum annealing edge treatment. The original (2 μm wide) junction had a very large critical current density of 1.2×10^6 A/cm^2 at 4.0 K. Wide-junction effects were seen over the entire temperature range. To optimize junction properties, the junction was narrowed to sub-micrometer size. The I-V characteristics and magnetic-field-modulation results showed that the narrowing process is effective for the fabrication of nearly ideal junctions, and I_CR_N product was 5.16 mV at 4.0 K. This implies that this type of HTS Josephson junctions should be made very narrow from the onset, especially if large characteristic voltages are required. Furthermore, we demonstrated the fabrication of IEJs on sapphire substrates, and the I-V characteristics showed RSJ like property at temperatures greater that 70 K. As a result, narrow IEJs on sapphire substrates will be very attractive for microwave to THz applications. Our next step is to make such junctions and to demonstrate sub-millimeter mixing.

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